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Particle Splitting for Monte-Carlo Simulation of the National Ignition Facility

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PARTICLE SPLITTING FOR MONTE-CARLO SIMULATION OF THE NATIONAL IGNITION FACILITY

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The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory is scheduled for completion in 2009. Thereafter, experiments will commence in which capsules of DT will be imploded, generating neutrons, gammas, x-rays, and other reaction products that will interact in the facility's structure. In order to understand and minimize the exposure of workers within the facility to prompt and delayed (activation) dose, we have developed a model for the facility using the three-dimensional Monte Carlo particle transport code, TART. To obtain acceptable statistics in a reasonable amount of time, biasing techniques are employed. In an effort to improve efficiency, we are studying the optimization of particle splitting using geometrically similar, but much simpler models. We are discussing our techniques and results.

I. INTRODUCTION

The National Ignition Facility's primary mission is to attain fusion ignition in the laboratory. This will provide the basis for future decisions about fusion's potential as a long-term energy source, about the Stockpile Stewardship Program without underground nuclear testing, and about high-energy-density science that will yield new insight into the origin of our universe.

In the attempt to produce fusion during the ignition campaign, 192 laser beams will irradiate the inside of a holhraum, creating x-rays that will compress the Deuterium-Tritium (DT) target, thus producing neutrons, gammas, x-rays, and other reaction products. The very high radiation fluxes created will result in a prompt dose and the neutrons interacting in the surrounding materials will activate these materials, thus resulting in a delayed dose.

We are developing a three-dimensional Monte Carlo particle transport model for the NIF facility to calculate, understand, and minimize the exposure to the workers within the facility, as well as to the instruments. We are using the Monte Carlo code TART, which was developed at the Lawrence Livermore National Laboratory.[1] We are presenting the challenges of deep penetration problems and the techniques we are using to solve them.

II. MODELING THE NIF FACILITY

The NIF facility is a large and complex structure (Fig. 1) that requires the development of efficient and precise models for its geometric and neutronic representation. The complicated nature of the facility results in a large number of boundaries in the neutronics model (Fig. 2), thus increasing the running time to obtain reasonable statistics. In addition, the large thickness of some areas of the structure such as the bay wall leads to a very significant running time increase to obtain reasonable statistics. We define that "reasonable" calculated data should be within ±%5 of the mean.

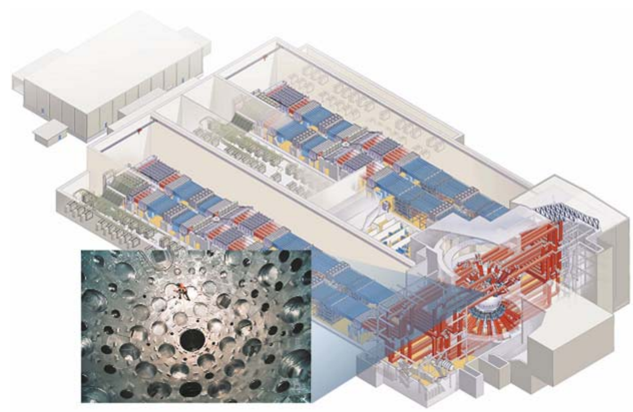

Fig. 1. The NIF facility, with a close up of a person working inside the target chamber.

Consequently, a statistically significant number of particles are unlikely to reach geometric regions of interest in the neutronics model without modeling many billions of particles. This is especially true when considering the outside of the bay wall (1.8 m of concrete). Without a variance reduction method, calculation of neutron and gamma fluxes in those areas would take from dozens to hundreds of days of running time using a common Linux or PC. We used a 1.9 MHz, 256 MB of RAM Linux-operated PC, and a 3.6 GHz, 2 GB of RAM Windows-operated PC.

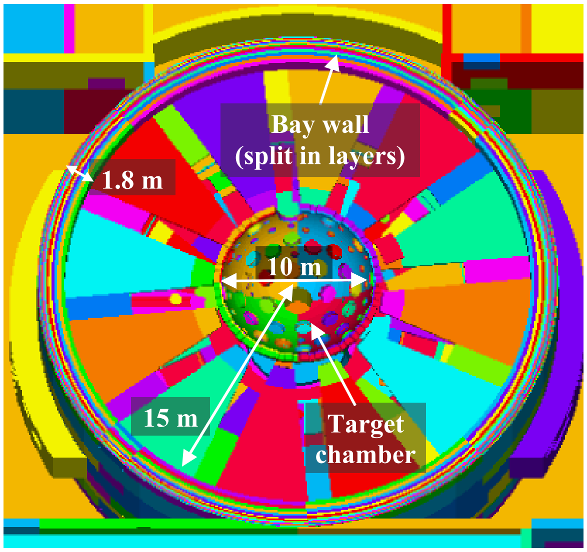

Fig. 2. TART model of the inside of the bay wall of the NIF facility, with the target chamber in the middle.

III. THE SPLITTING AND RUSSIAN ROULETTE TECHNIQUES

This work studies the optimization and quantification of particle splitting, a variance reduction technique that decreases the variance of a run, σ, or its relative error, R, while increasing its computational time, t. This splitting technique is described in several papers, books, and reports.[1-4] Geometry splitting associated with Russian roulette is one of the most widely used variance reduction techniques in Monte Carlo codes. When used effectively (i.e. splitting a volume in the right number of layers), this method causes a net increase in the figure of merit, FOM = 1/ (t R^2). The time it takes to reach the same precision in a result will therefore be decreased when using splitting.

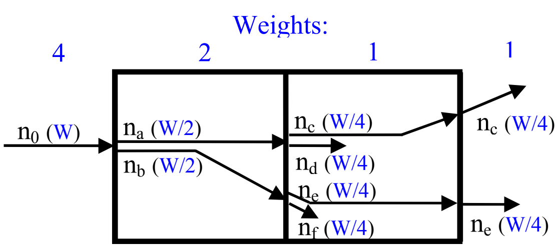

Fig. 3. Schematic of the splitting technique.

The splitting and Russian roulette techniques are represented in Figure 3, where a thick material is divided into 2 layers. A thick material corresponds to a thickness of at least several mean free paths of the incident radiation. For instance, the mean free path of a 14.1 MeV neutron in concrete is 8cm (a third of the primary neutrons will go through 8cm of concrete), and its half value layer is 5.5cm (half of the primary neutron population will reach 5.5cm in concrete). A good rule is to keep the population of tracks traveling in the desired direction more or less constant, thus for 14.1 MeV neutrons, we can expect the optimum layer thickness to be around 10cm. This value is higher than the 5.5 and 8cm previously mentioned because of the scattering that adds a significant number of neutrons to the primary flux.

In this figure, an incident neutron n_0 of weight W is split at the boundary crossing into two identical neutrons n_a and n_b (same energy, direction) having half the weight of n_0. The number of split particles and their weight are given by the ratio of weight associated with each volume of the problem. So for example n_a is split into 2/1 neutrons (n_c and n_d) each having the weight of n_a divided by 2/1, thus W/4. In TART, the number of split particles can only be twice or half the number of original particles, thus the ratio of weights of neighboring volumes must be ½, 1, or 2. Russian roulette is a technique used to terminate unimportant histories when the particle weight has fallen below some minimum value or its direction becomes statistically unimportant (n_f for instance). This technique decreases the number of particles that must be tracked further.

IV. QUANTIFICATION OF THE INCREASE IN EFFICIENCY WHEN SPLITTING

IV.A. The figure of merit

In order to measure the increase in the efficiency of a run when a 1.8m concrete wall is split compared to when it is not split, we use the figure of merit, FOM, of each run. The higher the FOM, the most efficient the run. Equations 1 and 2 gives the expression of the FOM and of the relative error, R, where t is the running time, σ is the variance of a run, and $\overline{x}$ is the mean value of the result.

$$\mathrm{FOM} = \frac{1}{R^2 t} \qquad (1)$$

$$R = \frac{\sigma}{\overline{x}} \qquad (2)$$

The decrease in running time when the wall is split is given by the ratio of FOMs, $\mathrm{FOM}_{\text{n layers}} / \mathrm{FOM}_{\text{1 layer}}$, which is equal to the ratio of computational times for low variances results (Equation 3).

$$\lim_{R\to 0}\left(\frac{\mathrm{FOM}_{\text{n layers}}}{\mathrm{FOM}_{\text{1 layer}}}\right) = \mathrm{cste} = \frac{t_{\text{1 layer}}}{t_{\text{n layer}}} \qquad (3)$$

IV.B. A simple TART model to test the splitting and Russian roulette techniques in the bay wall

As can be seen on Figures 1 and 2, the inside of the cylindrical bay wall is quite complex: the 10m diameter, 60cm thick (50cm of concrete and 10cm of Aluminum) target chamber is in the center, and multiple structures are in between the chamber and the bay wall (concrete floors, pipes, collimators, instruments, etc…).

We designed a geometrically similar, but much simpler model than the real NIF facility, with different splitting or no-splitting configurations for the concrete bay wall. We did not model anything inside the bay wall and changed the bay wall to a sphere. Also, to increase the number of neutrons reaching the bay wall, the diameter of the inside of the bay wall was reduced from a radius of 15m to 15cm, increasing the neutron flux by a factor of 10^4. These changes modify the absolute results, but they do not significantly modify the ratio of computing times between the splitting and no-splitting cases, which is what we are calculating. We will compare absolute results in a more complicated case in the next section.

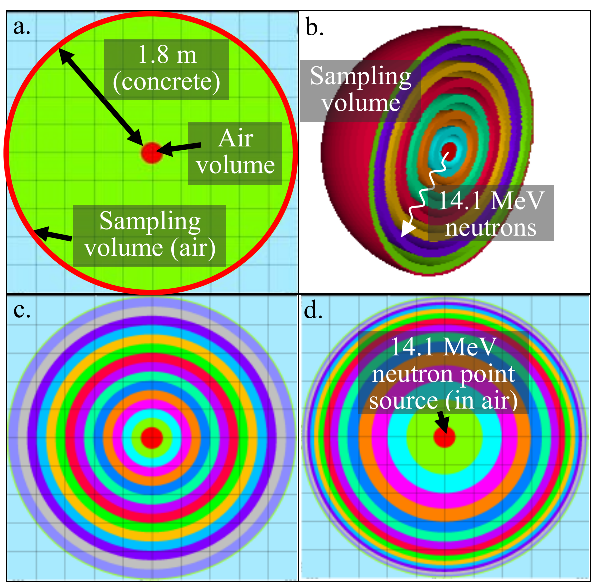

Fig. 4. 2D and 3D cross sections of the concrete bay wall that is not split (a), split into constant thicknesses (b and c), and split into exponential thicknesses (d).

Figure 4 presents the 3 cases that were modeled. Figure 4a is a cross-section of the “no-splitting” case, where the 15cm radius air volume is surrounded by a 1.8m shell of concrete. There is a point source of 14.1 MeV neutrons in the center of the air volume. Figure 4b is a 3D visualization of the “splitting” case where the concrete wall is split into 14 layers, which corresponds to 13cm thick layers. Only half of the 14 layers are represented in this figure to facilitate visualization. Results were obtained for several numbers of layers, from 5 to 22 layers, corresponding to thicknesses of 36.6cm to 8.3cm respectively. Figure 4c is a cross section of the same model as in Figure 4b, and Figure 4d represents the cross section of 14 exponential layers. The thickness d_n of the exponential layers were calculated using the formula $d_n = d_1\ e^{layer\#/5.5cm}$ so that the number of neutrons remains more or less constant through the wall.

IV.C. Results

Using these TART models, we calculated the energy deposited and the path length of neutrons and n-gammas in the sampling volume. The particle flux (cm^{-2}) can be obtained by dividing the path length of the particle (cm) in the sampling zone by the volume of the zone (cm^3). We used a Linux-operated PC (1.9 MHz, 256 MB of RAM) to run the cases where the 182.9cm bay wall is divided into 1, 5, 10, 12, 13, 14, 15, 17, 20, and 22 layers of constant thickness.

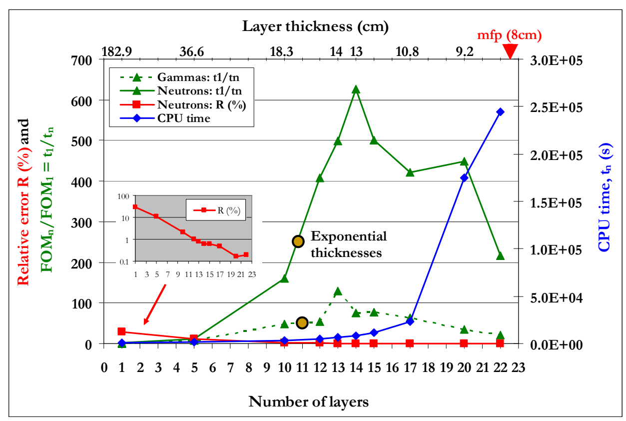

Fig. 5. Statistics of the $E_{deposited}$ by the 14.1 MeV neutrons (solid line) and by the neutron-gammas (dash line) in the sampling zone, after going through 182.9 cm of concrete, divided from 1 to 22 layers.

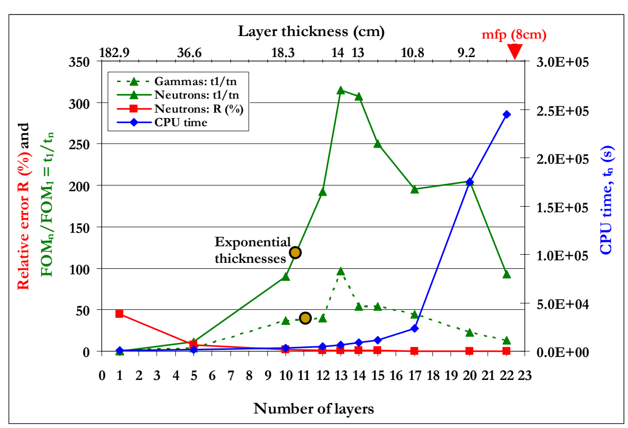

Fig. 6. Same data as in Figure 5 for the path length (thus the flux) of the 14.1 MeV neutrons (solid line) and the neutron-gammas (dash line).

Figures 5 and 6 provide the statistical parameters of the runs: the relative error, R (%), the running time, t (s), and the ratio of figure of merit for the n layer case and the 1 layer case (no splitting), FOM_n/FOM_1. This ratio is also equal to t_1/t_n. The values of R and t_n are for 1e6 source neutrons, and the values of the ratio FOM_n/FOM_1 were obtained so that all the results have a relative error of 3% or less. Figure 5 presents the statistics for the energy deposited by the 14.1 MeV neutrons and by the n-gammas in the sampling zone, after going through 182.9 cm of concrete, which is divided from 1 to 22 layers. Figure 6 presents the same data for the path length, thus for the flux.

The results show that for both neutrons and gammas, splitting the bay wall into 13 to 14cm layers is much more efficient than not splitting it. It is 626 times faster to obtain the energy deposited by neutrons when splitting the 182.9cm wall into 13cm layers. Similarly, it takes 315 times longer to obtain the neutron flux when there is no splitting. This ratio is a constant as long as the relative error stays low. Splitting the wall into exponential layers is more efficient that not splitting it by a factor of 38 to 251, but it is not as efficient as splitting the wall into layers that have the same ~13cm thickness. We checked these results with a 40cm concrete wall corresponding to five times the mean free path. The results were the same: splitting the wall into ~13cm layers was from 1.04 to 1.84 times more efficient. In the 182.9cm wall case, we also quantified the inefficiency of splitting a volume to obtain data in this same volume. It takes from 500 to 1300 times longer to obtain the energy deposited and the flux of neutrons and n-gammas inside the wall when the wall is split. Splitting is only efficient when the region of interest is outside the split volume.

IV. QUANTIFICATION OF THE DIFFERENCE IN ABSOLUTE RESULTS WHEN SPLITTING

We designed an asymmetric and more complex, but still simpler model than the real NIF facility, to calculate the difference in absolute values between the 13cm layer splitting and the no splitting cases. Figure 7 shows the 2D and 3D cross sections of the splitting TART model. The model used for the no-splitting case is the same except that the bay wall and ports are not split. The volume of air in the center is now 30cm in radius to allow 10cm radius open ports through the concrete wall. The ports are filled with air and are also split to respect the weight ratio between neighboring volumes that has to be ½, 1, or 2. These open ports are simple representations of the re-entrant tubes and collimators that are present in the NIF facility. Four sets of detectors were modeled outside the bay wall, each detector being a 15cm cube filled with air. Detectors 50 to 59 are used the measure the difference between the splitting and the no-splitting cases at several distances from a solid concrete bay wall. Detectors 60 to 69 measure the effect of an opening in the bay wall, especially the effect of particles scattering through layers of concrete and air. The geometry allows only a small fraction of primary neutrons to reach the detectors, forcing the large majority to scatter. Detectors 70 to 79 measure the effect of an opening in the bay wall associated with a 20cm backscattering slab of concrete. Detectors 80 to 89, 101 and 102 measure the effect of an opening in the bay wall followed by a 40cm aluminum scattering slab (80-89) and a 20cm concrete slab.

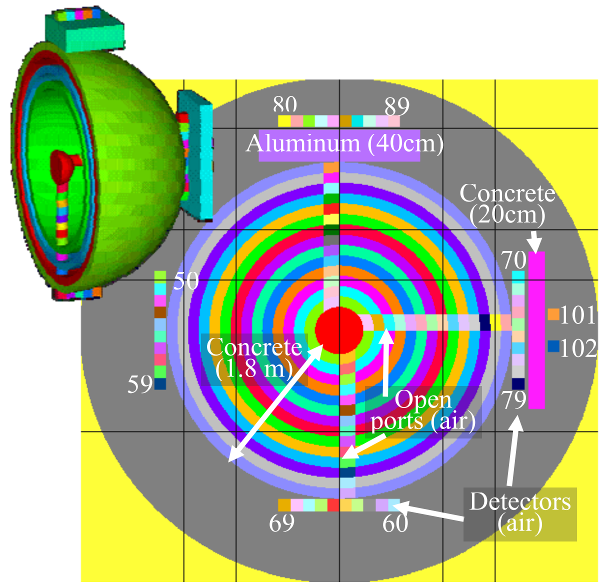

Fig. 7. 2D and 3D cross section of the TART model used to quantify the difference in absolute values between the splitting and the no splitting cases.

Figure 8 presents the absolute values of the energy deposited (solid symbols) and the path length (open symbols) of neutrons in the detectors using splitting (red symbols) or no-splitting (blue symbols). There were a total number of source neutrons equal to 2.28e9 n. in the no-splitting case and 5e6 n. in the splitting case. The relative errors of the results obtained in detectors 50 to 59 are up to 33% and were not brought down because of the extensive computational time it would have taken. Relative errors in the other detector's results remain under 7%. Results for n-gammas are not presented on this graph for a question of clarity but they are presented in Figure 9.

Figure 9 presents the percentage difference between the absolute results in the splitting case and the no-splitting case for both neutrons (red symbols) and n-gammas (blue symbols). Errors bars are not shown for the n-gammas results because they are smaller than the symbols. In addition, a dash line has been added to the path length results to help visualization. We can see that using the splitting technique lead to a difference of up to 8% in the energy deposited by neutrons (5% for n-gammas), and up to 5% in the neutron path length (3.5%

for n-gammas), thus in the particle flux. It is interesting to notice that splitting almost always underestimates results in the n-gamma case, whereas it varies in the neutron case. Also the dash line help to notice that there is a jump in the difference of up to 8% in detectors that are in front of the open ports (detector number ending in 4), probably due to the necessary splitting of the air in the ports.

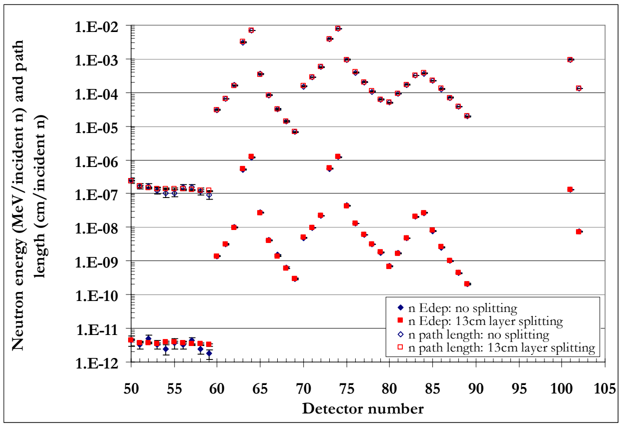

Fig. 8. Absolute values of the energy deposited (solid symbols) and path length (open symbols) of 14.1 MeV neutrons in detectors: 50's, 60's, 70's, 80's, 101 and 102.

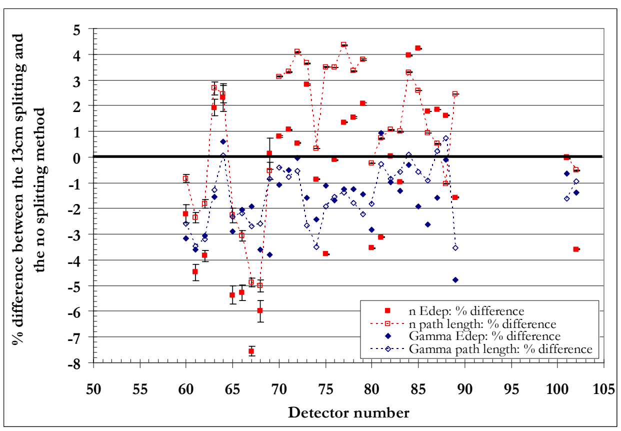

Fig. 9. Percentage difference between the absolute results (energy deposited and path length) in the splitting case and the no-splitting case for both neutrons (red symbols) and n-gammas (blue symbols)

V. CONCLUSION

We have confirmed that splitting the 1.8m concrete bay wall in 13cm to 14cm layers should not modify significantly the results when using the Monte Carlo code TART. The splitting and Russian roulette techniques are very efficient in terms of computational time, allowing to obtain the same relative error in energy deposited or path length for both n-gammas and neutrons in running times that are up to 626 times shorter than when the bay wall is not split.

ACKNOWLEDGMENTS

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